Final Report – AOARD 064040

Subject - Understanding the function of circular polarisation vision in mantis shrimps: building a C-Pol camera.

Duration - 1 year
Applicants - Justin Marshall
Location - The University of Queensland, Australia

General Introduction and project background (from proposal).

Mantis shrimps (stomatopods - Fig.1) are marine crustaceans with a visual system that has the potential to out perform all others, including humans. Using current AFOSR / AOARD funding, we are investigating their capabilities and aim to show how these animals solve visual problems such as object detection. Their compound eyes are each divided into 3 regions, the upper and lower hemispheres, that are of a relatively standard crustacean design similar to *eg* crabs, and the remarkable mid-band region (Fig.2). The mid-band contains neatly segregated zones for complex 12-channel colour vision and an astonishing polarisation system, the core of this study.

Fig.1 A mantis shrimp looking out from the front entrance of its burrow. This and other species live on coral reefs and in other shallow tropical waters.

From previous anatomical and behavioural work, we know that row 5 and 6 of the mid-band possess photoreceptors capable of polarisation sensitivity in 2 spectral regions (UV and blue/green - Fig.2). New evidence suggests that the blue/green system is tuned to circular polarised light (R in one row and L in the other, Fig.5).

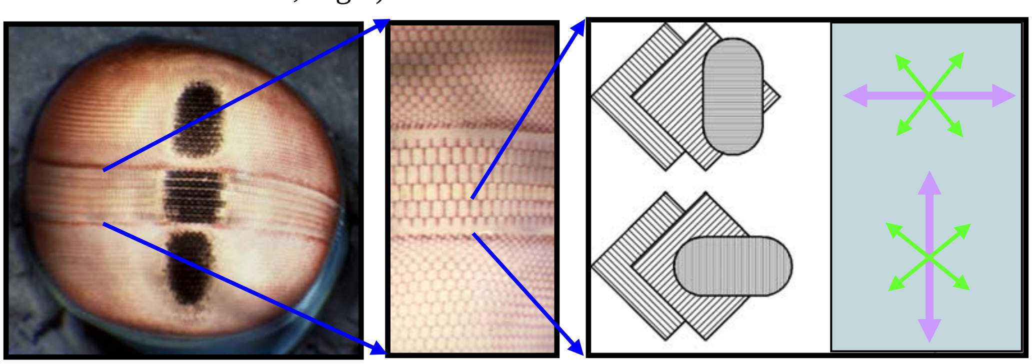

Fig.2 The stomatopod eye. The bottom 2 rows of the mid-band contain photoreceptors we think capable of polarised light vision, both linear and circular. Diagramatic representations of the photoreceptors within the eye (diamond and oval shapes) contain hatching in the direction of E-vector sensitivity - also shown to the right.

Report Documentation Page

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14. ABSTRACT
Report coversplans to construct a Mini-DV video camera capable of imaging C-Pol light, put this is an underwater housing and make field observations of both natural objects and man-made targets in the habitat of stomatopods. The camera system is a modified version of one already in use for imaging linear polarised light. Here a LCD switch-plate system, placed in front of the camera and capable of rotating the plane of incoming polarised light into 2 orthogonal directions (ie vertical and horizontal) has been synched to the frame rate of a video camera. As a result, alternate frames are views of the world through V and H polarising filters. Objects that appear to flicker (differ in intensity) between frames, are therefore reflecting or transmitting polarised light (seen differentially by the alternating V and H views of the world). This system will be modified using a switchable 1/4 wave plate and linear polarising filter to give frames seem through alternating R and L - handed circular polarising filters. Again, flickering objects or areas in frame varying in intensity between frames will indicate C-polarisation activity. Furthermore, analysis of alternate frames can be used to attempt image contrast enhancement, another possible advantage of C-polarisation vision.

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This is the first description of circular polarisation (C-Pol) sensitivity in any animal and is both a fascinating biological breakthrough and truly tantalizing for the field of biomimetics. We use circular polarising filters in photography and image enhancement to reduce glare and scattered light. Such technology is used extensively underwater for object detection but is seems that stomatopods already developed these tricks millions of years ago. What can we learn from them?

Objectives:

a) Construct a camera system capable of imaging R and L C-Pol light. b) Determine the use of C-Pol systems for mantis shrimps and judge usefulness for human applications. c) Move towards design of bio-mimetic circular polarised light imaging systems.

Potential Use:

Object detection through eg contrast enhancement and ‘invisible’ signaling systems.

Proposed methods and rational

I plan to construct a Mini-DV video camera capable of imaging C-Pol light, put this is an underwater housing and make field observations of both natural objects and man-made targets in the habitat of stomatopods. The camera system is a modified version of one already in use for imaging linear polarised light. Here a LCD switch-plate system, placed in front of the camera and capable of rotating the plane of incoming polarised light into 2 orthogonal directions (ie vertical and horizontal) has been synched to the frame rate of a video camera. As a result, alternate frames are views of the world through V and H polarising filters. Objects that appear to flicker (differ in intensity) between frames, are therefore reflecting or transmitting polarised light (seen differentially by the alternating V and H views of the world). This system will be modified using a switchable 1/4 wave plate and linear polarising filter to give frames seem through alternating R and L - handed circular polarising filters. Again, flickering objects or areas in frame varying in intensity between frames will indicate C-polarisation activity. Furthermore, analysis of alternate frames can be used to attempt image contrast enhancement, another possible advantage of C-polarisation vision.

References

Marshall, N. J., T. W. Cronin, et al. (1999). "Behavioural evidence for polarisation vision in stomatopods reveals a potential channel for communication." Current Biology **9**(14): 755-758.

Timeline

Camera development	July - December 2006
Field tests and image manipulation	January - March 2007
Final reporting and results	April - June 2007

(NB award was delayed by 15 months pushing this timeline on into 2007-2008)

Report

The camera and underwater housing has been constructed / put together and has been used in a number of applications (see below, Output 1, 2 and 3).

Underwater housing with removable internal filter sliders and HD Video camera with polarising LCD switch-plate system attached to front. When on the switch plates are synced to the camera frame rate giving alternate frames through vertical and horizontal linear polarising filter. When a ¼ wave plate is added, this changes to Left and Right circular polarisation.

Since this proposal, publications and publicity in the field of circular polarisation vision are as follows:

Tsyr-Huei Chiou, T-H, et al and Marshall, N.J 2008 Circular Polarization Vision in a Stomatopod Crustacean. **Current Biology**, 18, 429-434.

See - http://www.nature.com/nature/journal/v452/n7186/pdf/452390a.pdf
This and other commentary attached with report.

Publicity:

Australian ABC Radio
Australian ABC Radio Darwin
Australian Channel 10 News
Australian Channel 10 "Totally Wild"
International Current Biology Dispatches
International Nature Research Highlights
German Magasine "Zeitgeist"
Spanish Magasine "Apuntes"
USA NPR America "Science Friday"
Biophotonics International Magasine article
USA "Wired News"

In summary, this camera system now operating in the Marshall lab will enable a number of different lines of research into the nature of both circular and linear polarised light at high resolution.

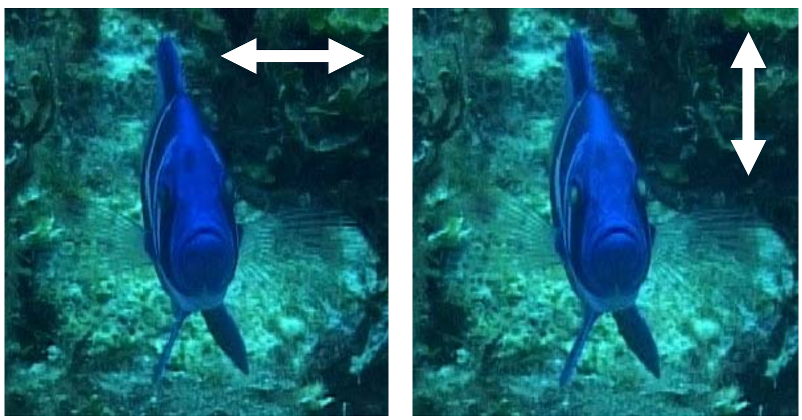
Output 1, contained within and explained by recent conference proposal:

AFOSR/AOARD/EOARD/ONRG/UQ funded conference held on Heron Island Australia ("New Directions in Research on Polarization of Light" June 9-13 2008), at which this camera system was showcased and used in the field. An extract from the conference proposal follows and demonstrates one direction that this contract has enabled the research to move towards.

"New Directions in Research on Polarization of Light" June 9-13 2008

Scientific Introduction

Of the fundamental properties of light - intensity, spectrum and polarization - light's polarization aspects seem the most mysterious to humans because our visual systems are unable to appreciate them without the assistance of artificial sensors. Polarization refers to the orientation of the electrical vectors (*e*-vectors) of photons within a beam or ray of light.



An indigo hamlet, Caribbean reef fish showing corneal polarization in sequential polarization images from AOARD/AFOSR funded work to Marshall/Cronin – note white corneas in vertical polarizing filter view and dark corneas in horizontal. This observation is a new image set from (July 2007) made available through camera systems developed between USA and Australia. The function of this phenomenon is largely unknown but its possible significance for both biological and camera vision in turbid media tantalizing.

When all of these vectors are parallel, the light is said to be fully plane polarized, or linearly polarized; if only some fraction of the *e*-vectors vibrate in a parallel plane, the light is partially linearly polarized; and if the *e*-vector orientations are completely random, the light beam is described as depolarized. Under certain circumstances, the axis of polarization is not constant, and instead rotates in a complete circle with the passage of each wavelength of light; in this case, the light is said to be circularly polarized, either right-hand or left-hand, depending on the direction of the rotation of the polarization axis. It is common for linear polarization and circular polarization to be mixed in a beam of light, creating a major axis of *e*-vector orientation together with a rotation of some of the polarization, in which case the beam is elliptically polarized. Thus, a full description of the polarization of a light source includes the degree of linear polarization, the axis of

linear polarization, the degree of circular polarization, and the direction of rotation of circular polarization. To repeat the point made above, human visual systems are insensitive to all of these features of light, but they are relatively easily visualized analyzed with appropriate optical instruments.

The light produced by most natural light sources (as well as the common artificial sources) has minimal, if any, polarization, but polarized light is nevertheless abundant in both natural and artificial photic environments. The polarization arises from reflection of light from dielectric surfaces, refraction by birefringent materials, transmission through dichroic materials, or scattering by dispersed, tiny particles in some medium suspending them (commonly air or water). Polarization properties of light are used by animals for orientation, navigation, contrast enhancement, object recognition, surface orientation analysis, and signaling. Humans actually use polarized light for many of these same applications. For example, polarization photography in fog or underwater can enhance object contrast and range of detection. Polarizers (both linear and circular) are used nearly universally in flat-panel displays to improve the display's contrast, and are essential for visualizing liquid-crystal panels. Specialized military applications are being investigated for recognizing objects, as well as for analyzing their surfaces and shapes. As with animals, polarization is used for signaling (primarily at microwave and radio wavelengths) to improve signal transmission and signal:noise ratios. Polarization's special properties continue to find new uses and have excellent potential for other as yet unforeseen technological applications.

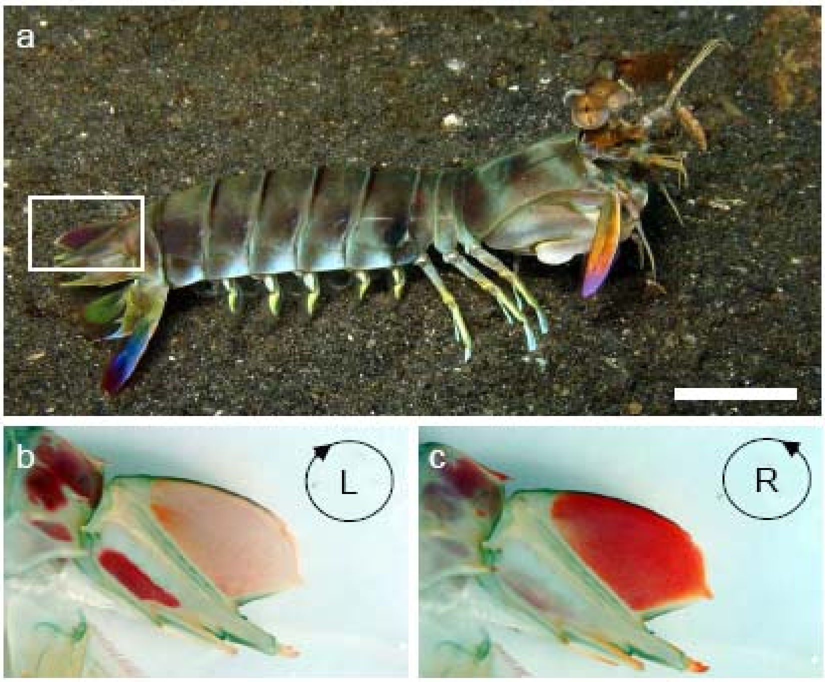
Research on polarized light has never been more vibrant than it is today, both in the engineering laboratory - where new applications are being sought by many scientists and engineers – and by biologists, who seek to understand how animals perceive, image, analyze, and use polarized light in their lives and to use biological systems to inspire new technical applications for polarization. Many of the laboratories worldwide that are at the forefront of polarization research are funded through the Air Force Office of Scientific Research. For instance, Engheta (University of Pennsylvania, USA) is studying techniques whereby polarization imaging can improve detection of cryptic objects as well as developing new camera systems for rapid capture of analyzed polarized images. Hawryshyn (Queens University, Canada) and Kamermans (Netherlands Institute for Neuroscience, Holland) are unraveling the means by which fishes analyze polarized light, both at the receptor level and at higher levels of processing in the retina and the brain. Warrant and his colleagues at Lund University (Sweden) are examining insect systems of polarized-light perception, vision, and processing with the aim of learning simplified neural-based solutions to problems of polarization analysis. The authors of this proposal, Cronin (UMBC, USA) and Marshall (University of Queensland, Australia) and their colleagues work on marine invertebrates to understand how these animals optimize detection and analysis of polarization, how they use polarization in their environment, and how they communicate using polarization as a secret channel. Work from all these laboratories and others is producing a flood of publications, often reporting completely unforeseen phenomena (such as the recent discovery that stomatopod crustaceans both perceive circularly polarized light and use it for signaling to each other).

Note that the previously unrecorded ‘filters’ in the eyes of the Indigo Hamlet are an observation made using this camera in linear mode. These ‘sunglasses for fish’ may be a new basis for polarisation vision if animals.

Output 2

Circular polarising signals in stomatopods and other animals.

Using the camera in C-pol mode, circular polarising signals are made obvious as they flicker or modulate at around 25Hz as the camera switches from Right to Left handed circular polarisation between video frames. This has enabled the discovery and characterisation of cuticular signals in stomatopods and beetles. (In fact previously noted but the significance was not realised - Neville, A. C. & Luke, B. M. (1971). Form optical activity in crustacean cuticle. J. Insect Physiol. *17*, 519-526).



Circular polarisation reflection from the tail of Odontodactylus cultrifer, here the male only possesses this reflection suggesting the possibility of sexual signalling? Whatever the function of the signal, it will be 'covert' and visible only to animals with C-pol vision. Currently this is limited to some stomatopods and the operator of this C-pol camera.

The search is now on for other animals in both marine environment and elsewhere with these signals. We have already identified many insects not previously known to posses this signal.

Output 3

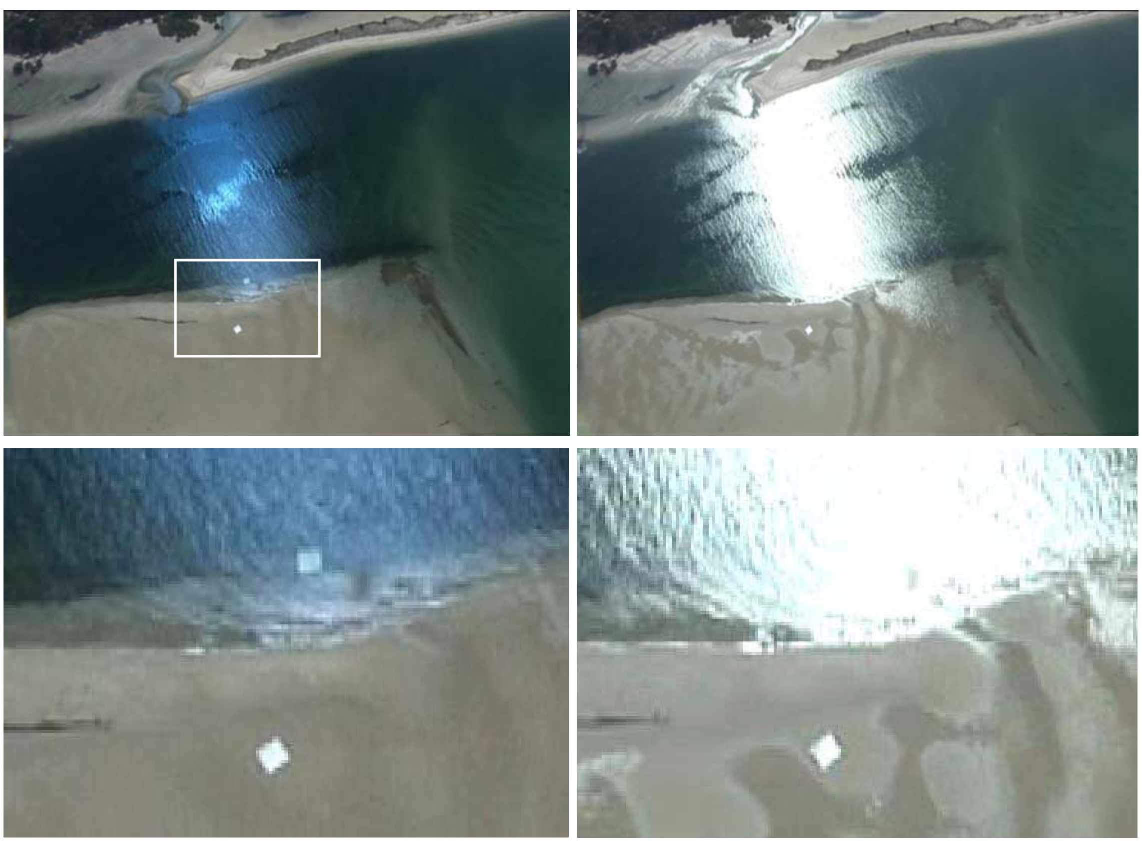
Prawns in Space – improving remote sensing.

The camera is currently being used in linear pol. And C-pol mode to investigate the removal of signal pollutant in shallow water remote sensing applications.

This feeds into a current body of work that is attempting to find ways of more effective environmental monitoring by using “Nature’s Technology”, that is bio-mimetic principles. As brief summary fo this project is as follows:

We aim to use what is known and what we will discover about animals’ visual systems to examine environmental health on The Great Barrier Reef and Moreton Bay. The innovative aspect of our approach is to examine the world with the eyes of birds, fish and invertebrates. Tricks animals employ to solve visual tasks will be implemented at scales of instrumentation from hand-held to remote sensing (RS) and used to address problems such as coral bleaching or algal blooms.

Very recent work has demonstrated the following:



Alternate linear pol. frames (Vertical left, Horizontal right) shot from a helicopter looking into shallow water of Moreton Bay. Underwater targets (5x5m white tarpaulins at 3 different depths) are placed to calibrate the contrast increase of having polarising filter at the right angle. At this angle to the sun, de-glint renders second target visible at waters edge.

A more thorough analysis of image improvement with and without glint and from different heights is underway to demonstrate and quantify the benefit of polarising systems in remote sensing.

Surprisingly, not many remote sensing devices take advantage of the contrast increase that polarisation can give (both linear and circular). Hopefully this sort of result will change the field?